

Managing the risk of uncontrolled flow of material (mudrush) at Argyle Diamond Mine

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Abstract

The Argyle Diamond Mine (ADM) was an underground block caving operation located in the East Kimberley region of Western Australia. The underground mine was operated from 2012 to December 2020. The mine is located in a tropical climate with very high monsoonal rainfalls, ranging from 600 mm to 1,800 mm during the annual wet season (December to March).

A combination of high monsoonal rainfall, significant groundwater inflows, cave connection to the pit surface, and a high proportion of fines in the cave column contributed to a high number of mudrush events over the production life of the Argyle underground mine. The term 'uncontrolled flow of material' (UFM) was used at ADM instead of mudrush. UFM events was one of the critical risks to personnel safety at the ADM block caving mine during its operation.

Over the life of the underground mine, more than 1,200 UFM events occurred, approximately 2 to 3 events every week during production of the cave. The UFM events typically ranged in size from 5 m³ to 4,000 m³. However, an extreme UFM event occurred in February 2020 that rapidly discharged 18,000 m³ material from the drawpoints, covering large sections of the extraction level and engulfing one of the underground crushers.

Despite the risk to personnel that UFM events posed at ADM, there were no recorded injuries over the mine life. The effective management of these events was critical to ensure the safety of underground personnel and to achieve production targets. This paper details the risk management controls that were put in place to manage the risk of UFM events at ADM.

Keywords: *block caving, uncontrolled flow of material, mudrush*

1 Introduction

The Argyle Diamond Mine (ADM) was an underground block caving mine that operated from 2012 to December 2020. The mine was situated in the East Kimberley region of Western Australia, 280 km south of Kununurra. A critical risk to the safety of underground personnel was the 'uncontrolled flow of material' (UFM) or mudrush from active drawpoints or within the material handling system. At ADM, mudrush events form a subset of the more generic classification of UFM events. A UFM was defined as any flow of material expelled from a drawpoint or other underground excavation that flows, uncontrolled, out of the excavation boundary. The flow rate can range from a slow ooze to an almost instantaneous rush.

The UFM risk existed at each drawpoint on the extraction level and in the vertical bins that formed part of the material handling system. Over the production life of cave, more than 1,200 UFM events occurred, or approximately two to three events every week. The UFM events typically ranged in size from 5 m³ (10 t) to 4,000 m³ (8,000 t), with an extremely large UFM occurring on 4 February 2020 that discharged 18,000 m³ (34,500 t) of material. The effective management of these events was critical to ensure the safety of underground personnel and to achieve production targets.

2 Mine layout and groundwater flow

The ADM extraction level is located 250 m below the bottom of the open pit (Figure 1a). The extraction level had 15 extraction drives (EDs) with over 150 active drawpoints. Figure 1b shows the mine layout of extraction drive from ED1 to ED15, the drawpoints and the tipples location overlying the underground crusher chambers.

The drawpoints located to the north of the cave were considerably wetter than the ones located in the south of the mine. This was due to the intersection of a number of water bearing faults and the predominant north to south groundwater flow along these structures. In addition, those drawpoints located on the periphery of the cave also displayed higher levels of water inflow.

Two crushers existed on the western side of the cave, Crusher 1 and Crusher 2. The northernmost crusher, Crusher 1, had the highest risk of a UFM event as its feed material was from the wettest drawpoints located in the north of the mine.

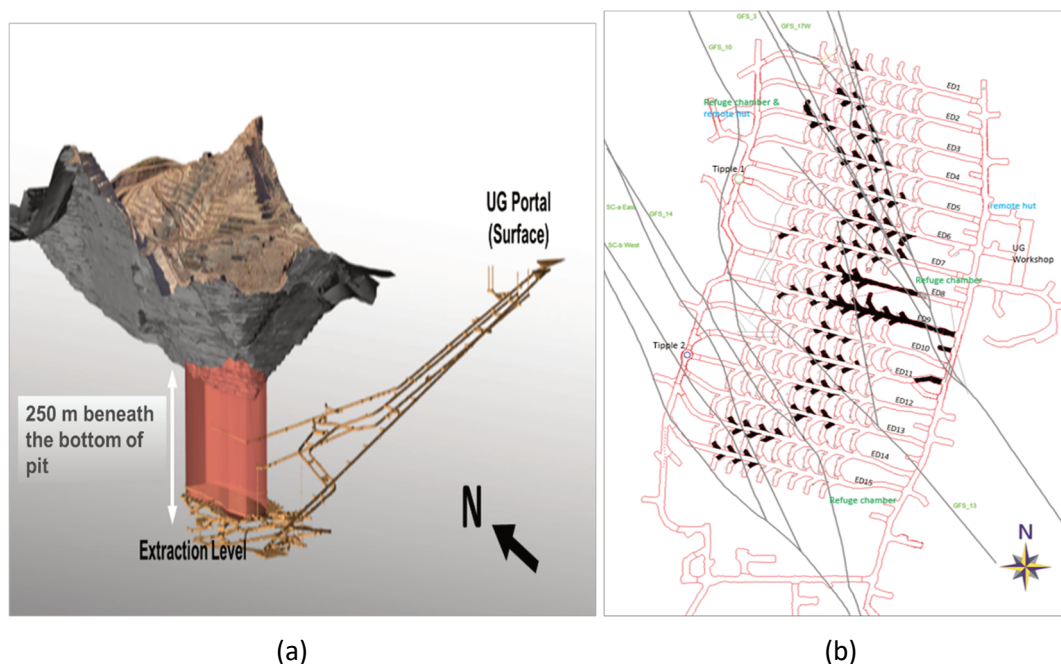


Figure 1 ADM mine layout. (a) ADM open pit and underground mines perspective view; (b) Plan view of the ADM extraction level showing primary faults (gap faults) and plugged drawpoints or drives (black shading)

3 Uncontrolled flow of material events at ADM

According to Butcher et al. (2000), four requirements must be met for a mudrush to occur:

1. Accumulation of fine material.
2. A source of water to allow the fines to become sufficiently moist to flow (under certain conditions).
3. Some disturbance to trigger the movement (drawpoint mucking, release of a hang-up, seismic event, or rapid inrush of water).
4. A connection to the underground workings.

The ADM orebody was predisposed to fines generation during caving due to the high clay content of the orebody, high degree of faulting and relatively low rock mass strength. There were also significant water inflows into the cave (particularly the northern drawpoints) from groundwater and from rainfall once the cave broke through to the overlying open pit. Water inflows into the cave ranged from 100 l/s in the dry season to 1,288 l/s during the wet season of 2020.

The weak rock mass and caving loads resulted in significant ground convergence on the extraction level of the cave. This resulted in large number of drawpoints being prematurely closed (early in the cave life) to retain access to the extraction drives and remaining drawpoints (Figure 1b). There were also long periods of no draw in some drawpoints while extensive ground support rehabilitation activities were completed. UFM management practices to reduce the wetness of material sent to the material handling system (discussed in Section 5) also resulted in differential draw between wet and dry drawpoints. The combination of closed drawpoints, rehabilitation activities, draw strategy for convergence management, and wetmuck blending increased the potential for localised, more intensive draw of a restricted number of drawpoints and a subsequent UFM risk.

The combination of significant water inflows, a high proportion of fines in the cave column and the challenges in maintaining uniform draw contributed to a high number of UFM events over the production life at ADM.

3.1 Uncontrolled flow or material from drawpoints

Over the life of the underground mine, more than 1,200 UFM events occurred, approximately two to three events every week during the mine's production life. The UFM events typically ranged in size from less than 5 m³ (<10 t) to 4,000 m³ (8,000 t).

The location of the events strongly correlated with drawpoints in the north of the mine that had the highest groundwater flow. The extraction drive ED1 made up 85% of the events followed by ED2 (5%), ED5 (5%), and ED4 (2.5%).

Each UFM was classified based on the distance the UFM travels from a drawpoint, and the approximate tonnage displaced. The UFM classification system consists of five categories (Table 1), ranging from Category 1 (smallest) through to Category 5 (largest).

Over 96.3% of the UFM events were classified as Category 1 and 2 events (1,162 events), 3% as Category 3 (36 events), 0.7% percent as Category 4 (seven events) and only two events as Category 5.

Table 1 ADM UFM spill classification

UFM category	Classification criteria	Approximate tonnage
Category 1	UFM travelled less than 5 m from the drawpoint source	10–200 t
Category 2	UFM travelled 5–15 m from the drawpoint source	200–500 t
Category 3	UFM travelled 15–30 m from the drawpoint source	500–1,500 t
Category 4	UFM travelled larger than 30 m from the drawpoint source, but did not reach footwall or hangingwall access	1,500–3,000 t
Category 5	UFM reached either footwall or hangingwall access	>3,000 t

The first UFM event at the mine occurred in September 2012, only several months after block caving production started, and prior to surface breakthrough. This was much earlier than expected and occurred in ED1 from the N3 drawpoint. The UFM discharged approximately 632 m³ (1,200 t) of wet material into the extraction drive (Figure 2). Fortunately, as the draw column was relatively low, the UFM travelled at a very slow speed and there was no injury or equipment damaged associated with the event.

The investigation into the event suggested the UFM was caused by a significant volume of fines that reported to the drawpoint combined with the groundwater. Due to the early stage of caving, the fine fragmentation was not due to secondary fragmentation of the caving process but believed the result of intersecting overlying faults.

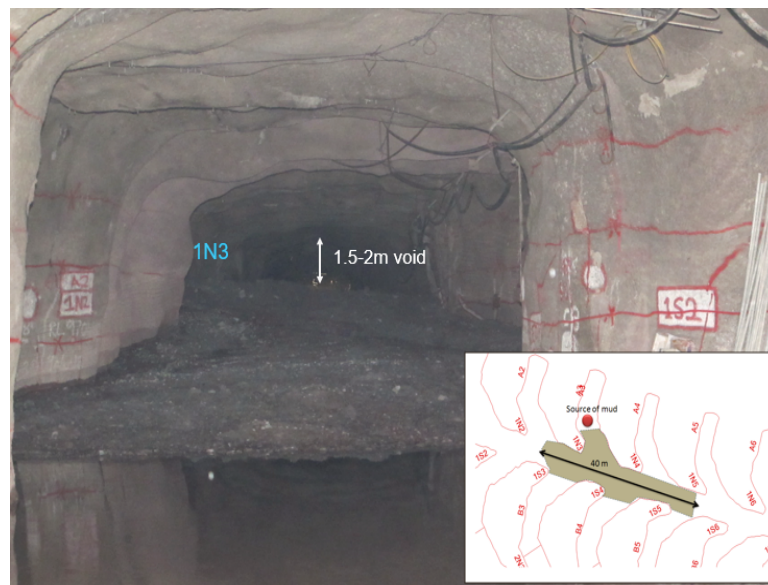


Figure 2 First UFM event from 1N3 drawpoint, ED1 on 19 September 2012, 632 m³

Following this first UFM event there was a consistent number of events over the operating life of the mine. The larger UFM category events predominantly occurred after the cave broke through to surface in 2013 (Figure 3a), with the severity increasing in the last year of operation with two category 5 occurring. Interestingly, the timing of UFM events (overall sizes) was not aligned with the wet season only, with a large number of events occurring in the dry season (Figure 3b). This was explained by the timing delay for the cave to drain, and draw strategies during the two seasons, which resulted in increased overall draw during the dry season.

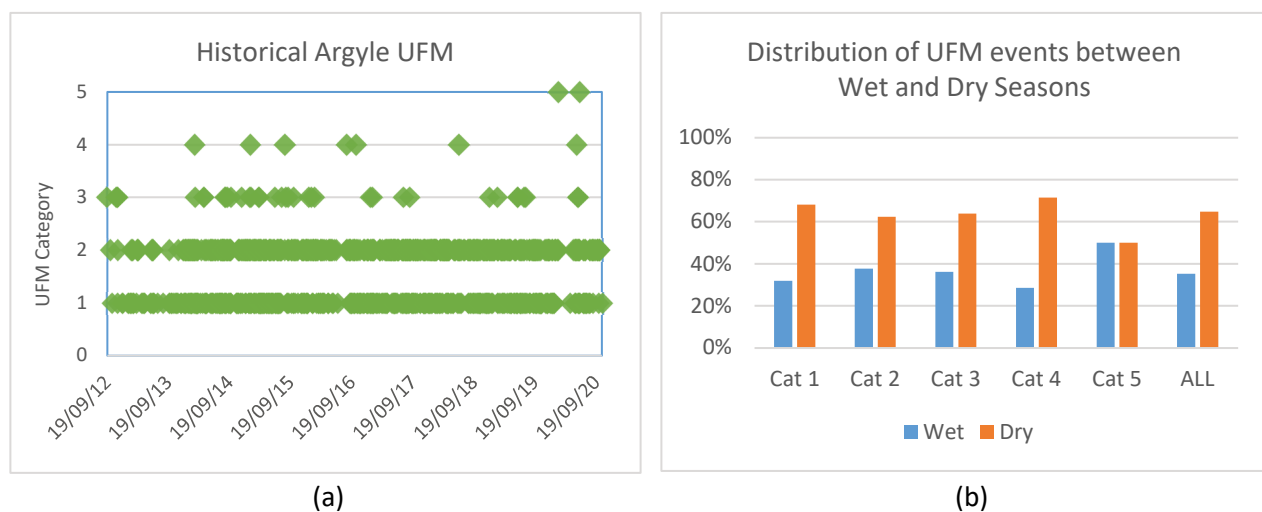


Figure 3 ADM UFM statistics (a) Historical UFM by category; (b) The comparison of UFM distribution in wet season (October to March) and dry season (April to September)

A key milestone in ADM's understanding of UFM risk was the learnings from the 30 January 2018 UFM event. A dry drawpoint 3N7 changed suddenly to wet, following a cumulative 50 mm of rain and the drawpoint material wetness changed within three hours after the rain event had stopped. This rapid change in wetness for a localised drawpoint was highly unusual.

The subsequent investigation identified the presence of a rathole immediately above the drawpoint. The cave was also likely to be in a fully saturated state (preceding cumulative rainfall since 1 October 2017, exceeding 200 mm) with limited capacity to absorb more water.

The rathole acted as a vertical funnel and provided a more direct connection from the drawpoint to the base of the open pit. These ratholes were often visible as a surface depression on the floor of the pit (as shown in Figure 4). The ratholes are created when there are high rates of differential draw between adjacent drawpoints. Drawpoint ratholes significantly increased the risk of UFM occurring at ADM due to the rapid change in conditions that can occur.

An intrush trigger action response plan (TARP) was developed to better manage the rapid change in conditions that can occur during periods of intense rainfall. A TARP defines the minimum set of actions required by workers in response to a deviation from normal working conditions. This TARP was a key control that ensured no personnel were exposed during the large February 2020 UFM event.

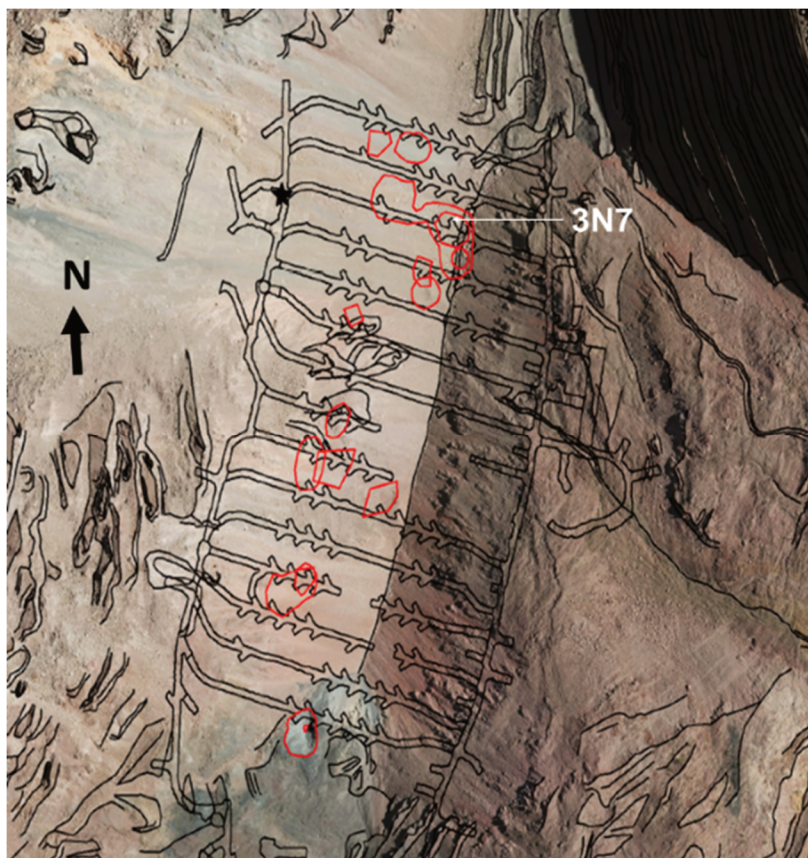


Figure 4 Plan view of the southern bowl bottom of the pit with the projection of underground extraction level. Red outlines were the historical ratholes mapped in the surface of the pit bottom in 2019

The largest UFM at ADM occurred in February 2020. The UFM displaced over 18,000 m³ (35,000 t) material from the drawpoints into the extraction drives. The UFM covered an area of more than 5,000 m² from ED1 to ED6, affecting half of the block cave operations (Figure 5a). The event was triggered by a significant rainfall event of 161 mm over four hours. This rainfall was above the one in 100-year intensity, frequency, and duration (IFD) design rainfall for ADM (111 mm rainfall depth over four hours). The rainfall event was the most significant in the underground operations' history (Figure 5b).

This significant rainfall event triggered the inflow TARP. The activation of this TARP requires exclusion zones to be established on the extraction level to protect people from any potential sudden inflow of material from the cave into the mine workings. The TARP was activated approximately four hours prior to the first UFM event, effectively managing personnel exposure to the intrush event.

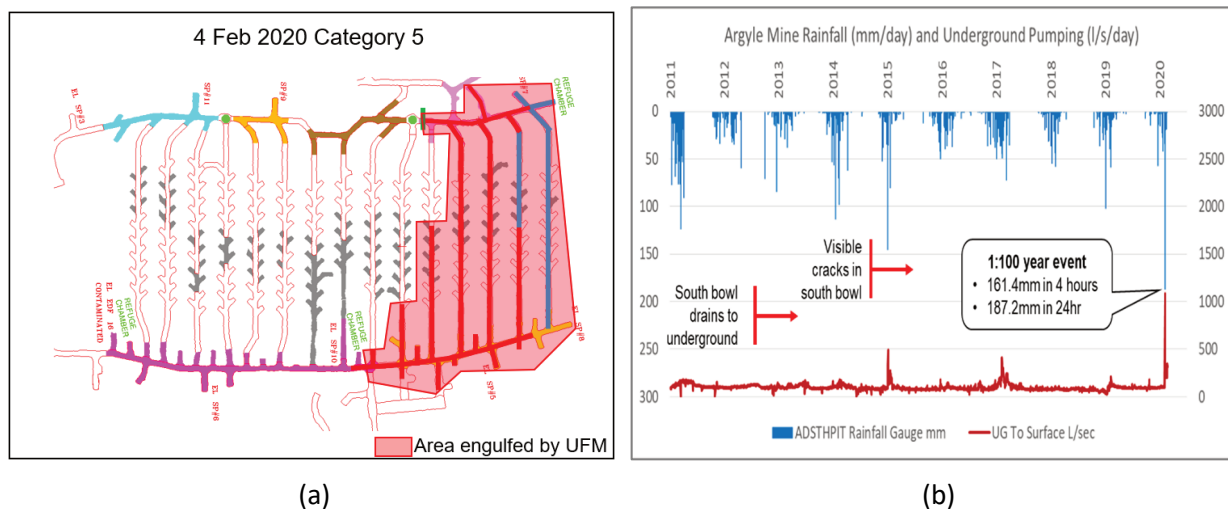


Figure 5 ADM 4 February 2020 UFM event. (a) Depiction of UFM in February 2020 that covered ED1-ED6 drives; (b) Historical hydrograph of rainfall and underground pumping to the surface that include the event on 4 February 2020

The investigation concluded that the UFM was a combination of at least two large UFM events from different drawpoints occurring approximately two hours apart. These drawpoints were all connected to the base of the open pit by ratholes. Video footage of the event showed the material in the drive moving at very high speed, much higher than underground equipment operating speed. The high observed speed of the UFM flow implied that the likely mechanism was the sudden collapse of hang-ups in the drawpoints. Prior to the rainfall event, there were two hung-up drawpoints in ED3 (assigned green and yellow classifications). It is likely that these were the sources of the UFM events, with subsequent inspection after clean-up showing that these hang-ups had both released, with one with sufficient force to completely remove the installed lintel steel cross beam supporting the back of the drawpoint (browset).

Although the TARP was effective in removal of personnel from the initial UFM event, it was evident from the incident review that the de-escalation to allow safe re-entry was not sufficiently addressed in the TARP for such a significant rainfall event. The TARP allowed access to the exclusion zone before the hazard of excessive water had been adequately managed. As result of this event an improved re-entry process was developed following the activation of the sudden inflow TARP to determine the timing of safe re-entry and commencement of operations.

It was encouraging to note that the revised controls were effective in managing personnel exposure to a large rainfall event (cyclone Esther) that occurred on 28 February 2020, and a Category 4 UFM in ED1 that occurred on 23 May 2020. The Category 4 event occurred within the first week of commencement of ED1 bogging following completion of clean-up activities from the 4 February 2020 Category 5 UFM.

A second Category 5 UFM event was recorded four months after the first Category 5 event on 9 June 2020. Unlike the event in February, it was during the dry season and not triggered by a rainfall event. The UFM, from a red DP in ED1, was fully contained within the ED1 exclusion zone with no personnel exposed to the UFM material. The event was most likely attributable to the extended time that ED1 drawpoints sat idle (four months) post the first Category 5 event. This was a result of the long clean-up time required to re-access the drive and the continued inflow of groundwater in the northern end of the extraction level.

Although the controls implemented were considered effective in managing personnel exposure, the decision was made to extend the tele-remote exclusion zone in ED1 to further reduce exposure.

4 Key controls to manage UFM risk from drawpoints

There were numerous controls implemented to manage the UFM risk at ADM. These can be grouped into seven main areas:

1. Drawpoint classification and inspection.
2. Exclusion zones.
3. Drawpoint bunding and stabilisation.
4. Draw control.
5. Dewatering.
6. Trigger Action Response Plans (TARPs).
7. Training and communication.

4.1 Drawpoint classification system and inspection

Classifying the UFM risk for each drawpoint is critical to the effective management of UFM risk. It is important to monitor risk changes within the drawpoint and to implement appropriate controls when UFM drawpoint risks are increased.

A similar classification system that was developed for Freeport's Deep Ore Zone Mine was adopted at ADM (Samosir et al. 2008). The classification shown in Table 2 uses the percentage of fine fragmentation less than 50 mm (P_{50}) and water content. The colour coding of green (low risk), yellow (medium risk) and red (high risk) indicates the level of UFM risk.

Laboratory testing on various drawpoint samples for moisture content suggested green classified drawpoints had moisture contents less than 6%, yellow drawpoints moisture contents ranged from 6–8% and the red classed drawpoints had moisture contents above 8%.

Table 2 ADM drawpoint classifications (modified after Samosir et al. 2008)

Fragmentation	P_{50} (include clay content or fault gouge)		
	$P_{50} < 30\%$	$30\% \leq P_{50} < 70\%$	$P_{50} \geq 70\%$
Wetness			
Dry (moisture content <6%)	X1 (green)	Y1 (green)	Z1 (green)
Damp (moisture content 6–8%)	X2 (green)	Y2 (red)	Z2 (red)
Wet (moisture content >8%)	X3 (yellow)	Y3 (red)	Z3 (red)

Using the classification system, weekly drawpoint inspections were completed and any drawpoint changes were communicated to underground personnel and used to inform any required controls. The inspection results were also used to guide blending management in the tipple.

It is not practical to measure the moisture content of each drawpoint. Instead, a qualitative visual assessment was used where drawpoints were classified as either dry, damp, and wet.

The classification system was an effective means to identify high risk drawpoints, with 95.8% of all UFM events coming from red drawpoints, 3.8% from yellow drawpoints, and less than 0.4% (≈ 5 events) from green drawpoints. The five events from green drawpoints were Category 1 and 2 events in the peak of wet season and were triggered during active bogging with limited exposure to personnel.

4.2 Exclusion zones

Exclusion zones are used to exclude all personnel from an area deemed high risk. There were three main exclusion conditions that were adopted at ADM for UFM management.

4.2.1 *Tele-remote loading exclusion zones*

Tele-remoting is a key control in managing the ADM UFM risk as underground personnel were removed from the risk area with the tele-remote operator being in an area outside the UFM risk zone. The availability and operability of the tele-remote systems is important to ensure the drawpoint risk is controlled and managed.

These zones are created when a red drawpoint (high UFM risk) is to be bogged. The exclusion zone is typically applied to the whole extraction drive length but also based on the largest observed UFM travel extent (if UFM travels exceed the drive). In this exclusion zone, the location of tele-remote loader mount/dismount area, drawpoint target, and dumping point are included. The zone is controlled by laser barriers, flashing red lights and numbered hazard signs.

4.2.2 *Exclusion zone on back-to-back drawpoint (sister drawpoint on the same drawbell)*

This exclusion zone is applied when a yellow (moderate risk, manually bogged with experienced operator) drawpoint is being bogged. The exclusion zone is in the extraction drive where the sister drawpoint of the yellow drawpoint is located. The concern is that bogging of the yellow drawpoint may initiate a UFM in the sister drawpoint (within in the same drawbell) where there may be personnel working.

4.2.3 *Exclusion zone under sudden inflow of TARP*

This exclusion zone is applied for the whole underground mine when the sudden inflow TARP is activated. The sudden inflow TARP activates during a significant high rainfall event. The exclusion zone requires underground personnel to evacuate to the surface and the underground tag board must be closed.

4.3 Drawpoint bunding and stabilisation

Drawpoint bunding standards were introduced in 2013 to mitigate the exposure hazard to personnel working in the extraction drives. The drawpoint bunding standard defines a minimum bund height of 1.5 m, wall to wall, made from dry coarse material (to allow drainage) and must have an adequate catchment area. For red drawpoints, a 'super bund' with a minimum height of 2 m was required.

In the case of red drawpoints, the bund was stabilised by spraying a 75 mm thick layer of 40 MPa fibre-reinforced shotcrete (FRS) to the front face. The FRS was tied into the drive walls and brow, with the lower part of the bund face not sprayed (0.5 m from the floor) to allow water drainage. An example of stabilised drawpoint rill is shown in Figure 6.

All stabilised drawpoint bunds were inspected weekly to assess any changes such as cracking of the FRS. No failure of the stabilised high risk drawpoints occurred at ADM.

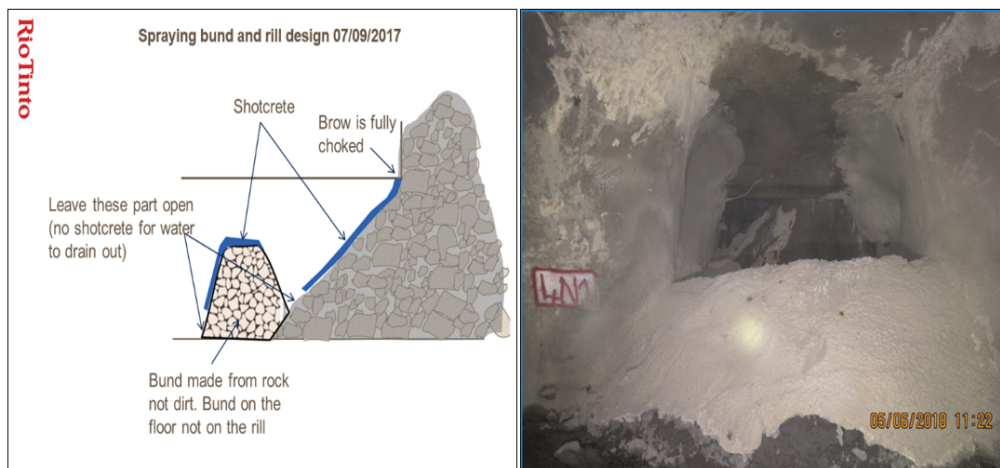


Figure 6 Stabilising a red drawpoint for rehabilitation

4.4 Draw control

Consideration of the UFM drawpoint risk was used to develop the daily draw order strategy which detailed the draw order and tonnage from each drawpoint. This considered current drawpoint UFM status, historic draw, availability of adjacent drawpoints, and presence of ratholes.

Polymathian's ORB software was introduced in 2019 to automate the loader dispatch. This resulted in improved compliance with the plan draw order and better management of the blending of wet material. (Donaldson et al. 2020).

Draw control management included several operational controls that were embedded in site procedures. These included:

- All red drawpoints are bogged by tele-remote equipment with exclusion zones in place.
- Yellow drawpoints are only bogged by experienced operators deemed competent in bogging wet drawpoints.
- When drawpoint conditions deteriorate, all operators are expected to stop the draw, install bunds and report the change in condition to the shift supervisor. If required, shift supervisors escalate to the wetmuck team.
- The tele-remote plan (TRP) is prepared by the hydrogeologist. The TRP contains the instructions of which tele-remote systems to use, drawpoint target, dumping point and other specific instructions. The tele-remote plan is reviewed and approved by the mining manager, foreman, and the electrician.
- Hang-ups in the drawpoint present a particular high risk scenario. If the hang-up suddenly lets go it can trigger a UFM event. When a hang-up occurs, a series of steps is implemented to manage the exposure. This includes increased bogging of the back-to-back (sister) drawpoints to attempt to dislodge the hang-up. This is followed by remotely operated water cannon and the last resort is by securing the drawpoint (with bunds and spray shotcrete) and using manual hang-up remediation such as drill and blast.

4.5 Dewatering

Several borehole dewatering programs were attempted in the early days of production to try to reduce the groundwater inflows in the cave column. Unfortunately, these were unsuccessful due to poor ground conditions.

The primary mechanism adopted to dewater the cave was via active bogging of the northern ED1 drawpoints. This was found to be an effective way to reduce the migration of water further south across the footprint, given preferential north–south groundwater flow. Although this increased the risk of UFM events in ED1, this was effectively managed by having this extraction drive under full tele-remotes with no exposure to personnel.

To minimise ingress of surface runoff water, diversion bunds were implemented on all access points to the pit. An in-pit pump system was also maintained in the northern end of the pit to ensure no water presented into the underground workings.

4.6 Trigger action response plan (TARP) for intruder

The inrush TARP was developed to manage the risk of rapid, sudden UFM risk changes across multiple drawpoints due to high rainfall intensity. The TARP is only activated in the wet season when the cave reaches a critical moisture saturation limit. At this critical limit, surface water is observed to pass through the cave column and flow more readily from the drawpoints. Past analysis indicates that this saturation limit is achieved when preceding cumulative rainfall from 1 October (start of the wet season) has reached 200 mm. Before this saturation limit, it was assumed any rainfall runoff is absorbed by the cave material and does not make a material difference to drawpoint wetness.

The TARP uses trigger levels for rainfall amounts over set time periods. These are 25 mm in one hour, 40 mm in two hours or 50 mm in three hours. When the trigger points are exceeded, all underground personnel are evacuated to surface and the tag board cleared. The intrush TARP is connected to a rain gauge located at the top of the open pit and automated in the mine control system with a display and audible alarm (Figure 7).

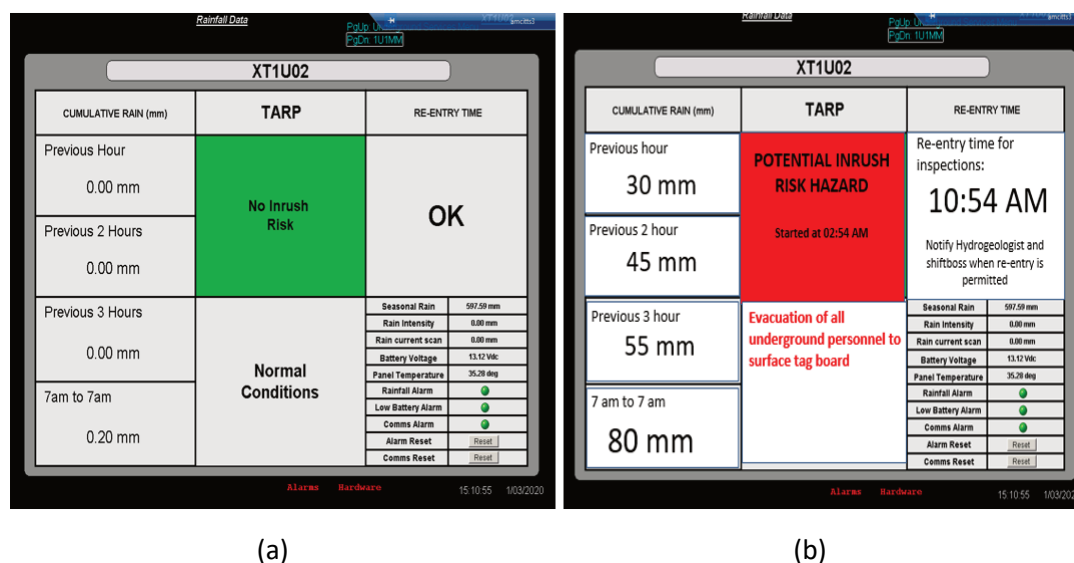


Figure 7 The inrush TARP display automated in mine control system. (a) Example of TARP on normal conditions; (b) Example of TARP display shows an evacuation was initiated due high risk of inrush

Re-entry to the mine will only occur:

- After a minimum 8-hour exclusion time/evacuation time and a minimum of 8% of the water from the rain event is accounted for in the underground inflows.
- Mining manager to approve the re-entry plan provided.

The mine water balance was maintained to quantify the inflow, outflow and water retained in the cave. The water inflow was calculated from the rainfall measurements over the surface catchment area. Water outflow from the cave was measured by the underground drainage and pumping system. Back-analysis and review

of the flows indicated that water outflows would stabilise to normal background levels after about 8% of the inflow volumes had entered the underground drainage system. This formed the basis of the re-entry TARP.

4.7 Training and communication

Training of underground personnel on UFM risk awareness at ADM played a key role in successful UFM management. The training ensured underground personnel could identify the UFM risk and recognise changes within the drawpoint. Facilitated by the senior hydrogeologist, the awareness training was completed as part of the underground induction, with refresher training completed annually. The training included detailed and practical identification of the risks on the extraction level. This, in communication with TARPs, enabled operators to make quick decisions if conditions at the drawpoint changed.

Changes to the UFM risk of a drawpoint can occur quite quickly. Ensuring this change is communicated to all underground personnel with potential exposure to the UFM is crucial. To achieve this there are several levels of communication including pre-start meetings, shift sheets, radio communications and the wetmuck status boards.

Arguably, the most critical is the wetmuck status board. The wetmuck status boards were installed at every extraction drive access containing the latest UFM risk levels in the drawpoint (Figure 8). This information is updated every time there is a change to the drawpoint UFM risk status. As part of the process of accessing the extraction drives, the underground personnel must review the wetmuck status board.

DRAWPOINT STATUS INFORMATION					
ED:	ED1		Update:	15-06-2013	
DPT	UFM Risk	Status	DPT	UFM Risk	Status
N1	Y	OS	S1	Y	OS
N2	R		S2	Y	OS
N3	Y	OS	S3	Y	OS
N4	R		S4	G	
N5	G		S5	G	
N6	G		S6	G	
N7	G		S7	G	
N8	G		S8	G	

UFM Risk	Status
Green Class Drawpoint	HU Hang-up
Yellow Class Drawpoint	OS Oversize
Red Class Drawpoint	CI Cluster Hang-up
	RH Rehab
	X Closed

Figure 8 Example of UFM status board in 2013 at the extraction drive 1 (ED1). Due to ED1 having two reds at that time, all drawpoints were drawn using tele-remote loader and no pedestrian access to the drive was permitted

5 UFM risk in the crusher

Two underground crushers were used at ADM (Crusher 1 and Crusher 2). The loaders tip material from the drawpoint into the crusher tipples. The material then progresses to the coarse ore bin, the apron feeder, and the crusher bowl in the crusher chamber area. UFM events can occur when fine, wet material is tipped into the tipple/coarse ore bin and flows out over the apron feeder.

Three major UFM events occurred in Crusher 1 over the life of the underground operations. The timing of these were: April 2014, December 2014, and April 2019. Note that Crusher 1 is located closest to the drawpoints with the highest groundwater inflows. Following the April 2014 UFM, a blending control program

was established to manage the mixing of wet material with dry material at the tipples, to keep the ore material in the crusher below a certain wetness.

The event on April 2019 was the largest UFM in the crusher with approximately 150 m³ of material spilling over the apron feeder and onto the surrounding crusher walkways and infrastructure (Figure 9). The UFM stopped the operation of Crusher 1 for three weeks. Although there was no exposure to personnel with an effective exclusion in place on the crusher level, it had a significant impact on underground production.



Figure 9 UFM in Crusher 1 on 23 April 2019 that covered the chamber. UFM estimated to be 150 m³ (300 t)

5.1 Crusher blending management

Blending management between wet and dry material tipped into the tipple has been in place since 2014. Past observations and benchmarking suggested the minimum blending ratio in the tipple is 2:1 dry to wet. The drawpoint classification is used to indicate the wetness levels; green = dry and yellow/red = wet.

Initially, blending management was the responsibility of the loader operators in combination with mine control. While this system worked well for most of the time, there were three crusher UFM events indicating that the process was not entirely effective in managing these events in the material handling system. A review of the incidents indicated that the blending control was reliant on effective communications between operators being in place to manage the blend.

A major improvement was made to the blending control by developing an automated real-time blending monitoring system. The system used the wetness of the drawpoint and the real-time production information to calculate the rolling average wetness of the material that tipped into the tipple. The Polymathian dispatch software ORB was used to calculate and visualise the blending occurring in the tipple and calculate future bogging dispatches to control the wetness (Donaldson et al. 2020).

The monitoring system included two audible alarm levels to control blending deviation. If the wetness of material in the tipple exceeded 35%, a level 1 alarm was activated. This was a trigger for mine control to review and adjust the loader bogging locations to reduce wetness of the blend. A level 2 alarm was triggered when tipple wetness exceeded 50%. If this alarm occurred, mine control would stop all loaders and notify the shift supervisor. The re-starting of wet material tipping only occurs once the wetness level in the tipple is below 35%.

This system was a significant improvement, removing the reliance on operator communications. Since the automated blending implementation there were no UFM events in the crushers.

6 Lessons learnt from ADM UFM management

It was identified early in ADM's mine life that methods that were successful at managing UFM events at other mines (Butcher et al. 2000) such as dewatering and applying interactive draw to minimise discharge of fines could not be easily achieved. Early groundwater ingress interception programs were unsuccessful due to poor ground conditions, and poor ground conditions caused the early closure of many drawpoints which made interactive draw difficult.

Instead, operational controls were developed based on the ongoing learnings from each UFM event. Some of the key learnings from events included:

- It was not possible to manage the groundwater inflows through dewatering bores. Alternative controls were required including early implementation of tele-remote loading to manage exposure of underground personnel.
- Maintaining consistent bogging in ED1 was an effective strategy to limit the migration of groundwater further south in the cave.
- Drawpoints often changed UFM classification. Routine drawpoint inspection, classification, and effective communication of the drawpoint status is a key component of effective UFM risk management.
- Underground operators need to be well trained in assessing drawpoint wetness, and know how to respond when conditions change quickly.
- Bunding was an effective control to prevent UFM events occurring when not being bogged. It is important that the bunds need to be designed and implemented correctly. Bunding standards are required for ensuring this compliance is achieved.
- High rainfall events can cause sudden and significant changes to the drawpoint UFM risk. A Trigger, Action and Response Plan (TARP) that covers both escalation and de-escalation triggers is a critical control to safely manage these situations.
- Awareness that localised draw can form ratholes connections to surface which significantly increases the UFM risk at ADM, particular in periods of high rainfall.

7 Conclusion

The ADM underground block caving operation faced many challenges with managing the risk of the UFM events from drawpoints and crushers. With an average of three UFM events every week over nine years, UFM events represented one of the highest risks to underground personnel safety.

Despite the everyday risk to personnel that UFM events posed at Argyle, there were no recorded injuries over the mine life. This is a proud achievement and testament to the effectiveness of the controls implemented. They were critical to ensure the safety of underground personnel while achieving production targets.

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